Bulletin of the Seismological Society of America, 92, 1, pp. 61–66, February 2002

Surface Rupture and Slip Distribution of the 12 November 1999 Düzce Earthquake (*M* 7.1), North Anatolian Fault, Bolu, Turkey

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Abstract The 12 November 1999 earthquake (*M* 7.1) occurred on the Düzce fault, a splay of the North Anatolian fault in the Bolu basin approximately three months after the 17 August 1999 (*M* 7.4) earthquake. The surface rupture was 40 km long, and the maximum right-lateral offset was 500 ± 5 cm, averaging 300 cm. The 9 km of the westernmost part of the rupture along the southern margin of the Eften Lake had a 350-cm maximum vertical displacement (normal faulting), some of which was already ruptured during the 17 August 1999 event with few tens of centimeters. The surface rupture has a generally simple narrow deformation zone of 0.5–5 m, however, in some places, it widens to 50 m. Transtensional and transpressional structures were observed within releasing and restraining step-over areas respectively. The larger dextral offsets on some streams indicate previous events. The dextral slip measurements along the rupture reflect a symmetric distribution. The eastern connection of this rupture zone with the main trace of North Anatolian fault remains unclear because the Bakacak and Elmalik fault, which are connecting faults, had no surface rupture.

Introduction

The 12 November 1999 Düzce earthquake (*M* 7.1; USGS, KOERI) occurred on the western part of North Anatolian fault nearly three months after the İzmit earthquake (*M* 7.4; USGS) and resulted in approximately 900 deaths and 3000 injuries. The Düzce earthquake somehow was expected (Barka, 1999) for three reasons: (1) this was the only segment that had not ruptured in this section of the North Anatolian fault; (2) the slip distribution of 1944, 1957, 1967, and August 1999 earthquakes (Barka, 1996; Barka *et al.,* 1999) indicated that there was at least a 2- to 2.5-m slip deficit in the area; (3) the 17 August 1999 earthquake increased the failure stress on this segment (Hubert *et al.,* 2000; Parsons *et al.,* 2000).

These two earthquakes are considered as a whole although the Düzce earthquake occurred later at the eastern continuation of the İzmit earthquake; they formed as a result of a westward migrating earthquake sequence that formed after the 1939 Erzincan earthquake (Fig. 1). The simple trace of the North Anatolian fault between Erzincan and Bolu splays into two strands westward beyond Bolu (Fig. 1). The

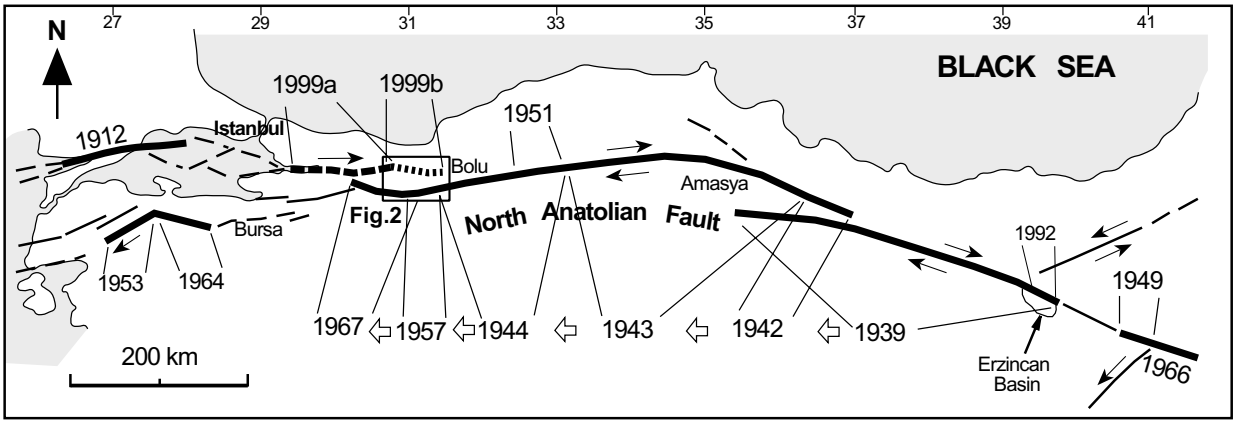

Figure 1. The westward migrating earthquakes since 1939 along the North Anatolian fault.

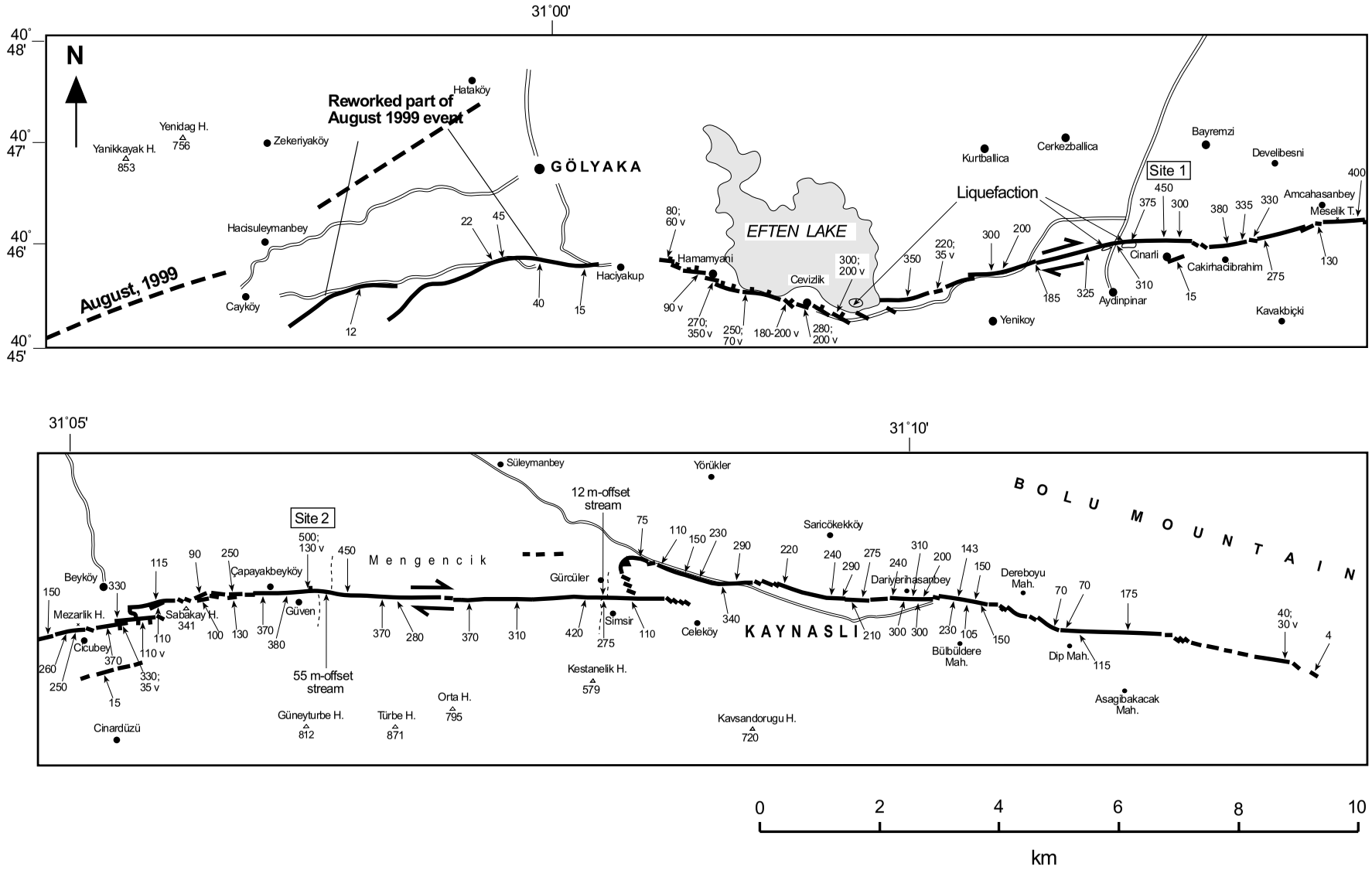

Figure 2. Surface rupture of 12 November 1999 Düzce earthquake. Numbers with arrow indicate lateral displacements; v, vertical separation.

southern strand goes into the Mudurnu valley, and the northern strand forms the Düzce–Hendek fault in the north surrounding a crustal block called the Almacık block. In the 17 August 1999 event (*M* 7.4) at least 140 km of the northernmost branch was ruptured between Karamürsel and Gölyaka (Barka *et al.,* 1999). In this article we present the rupture geometry and slip distribution along the rupture zone of the 12 November Düzce earthquake.

The Surface Rupture of the Düzce (*M* 7.1) Earthquake

The Düzce earthquake formed a 40-km-long surface rupture zone. There is a 4-km releasing step-over at the eastern end of the August surface rupture around Eften Lake. The surface rupture began in the eastern end of the Karadere valley, 5 km west of the Eften Lake, with 10–50 cm dextral offset that was overlapped with the eastern end of the 17 August earthquake (Hartleb *et al.,* 1999). The general trend of the surface rupture of Düzce earthquake is almost east–west; however, it varies between N75°W and N75°E. The maximum vertical displacement along the southern margin of the Eften Lake was 350 cm, and an additional 300 cm of right-lateral offset was also measured (Figs. 2 and 3). Three liquefaction events were observed around Cevizlik and Çınarlı villages, diameters ranged between 0.7 and 12 m, and heights ranged from 8 to 50 cm (Fig. 2).

The amount of right-lateral offset increases toward the central part of the rupture zone. A 450-cm offset is measured around the village of Çınarlı (Figs. 2, 4, and 5; site 1). The maximum offset is 500 ± 5 cm around Güven village (Figs. 2, 6, and 7; site 2). The offsets were clearly observed and measured on roads, fences, tree lines, rivers and streams, and buildings (Fig. 6). The trace of rupture was located in a narrow deformation zone changing between 0.5 and 50 m (mostly 2–5 m) in width. There were en-echelon tension cracks oriented between N50°W and N75°W in a relatively broader deformation zone. Two restraining step-over areas, 200 m in the east of Cicubey and 500 m around Gürcüler village, were mapped. In these areas, the connecting segments were made up of thrust and en-echelon thrust faults (Fig. 2). Toward the east, the rupture zone cuts the old main road, and the amount of displacement varies between 150 and 310 cm until Dereboyu village, located in the eastern part of Düzce–Kaynaşlı plain (Fig. 2). In this area, surface rupture cuts the viaducts of the new highway, which is under construction, with 150-cm offset, causing extensive deformations on the legs of the viaduct. The amount of offset further diminishes to a few tens of centimeters or less on the

Figure 3. Vertical displacement in the south of the Eften Lake.

Figure 4. Offset garden fences around Çınarlı village (450 cm).

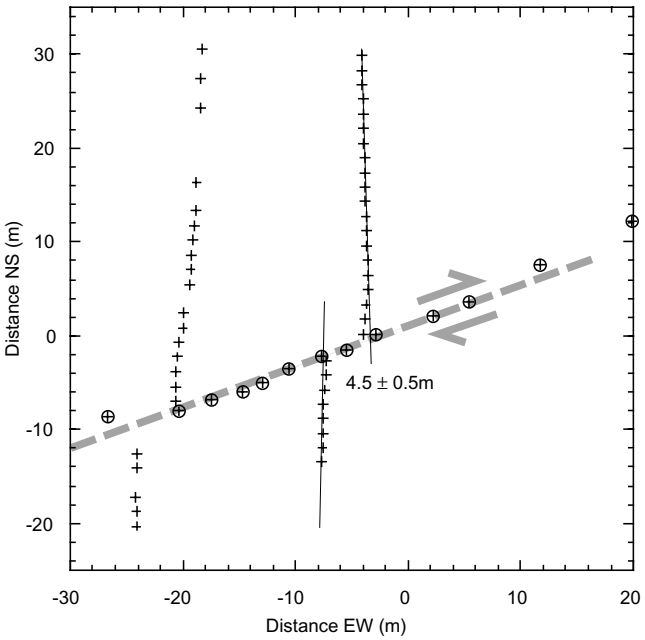

Figure 5. Survey with total station on garden fences around Çınarlı village (site 1, for location see Fig. 2).

Figure 6. Maximum dextral offset site on Düzce earthquake surface rupture (Guven village road; 500 ± 5 cm).

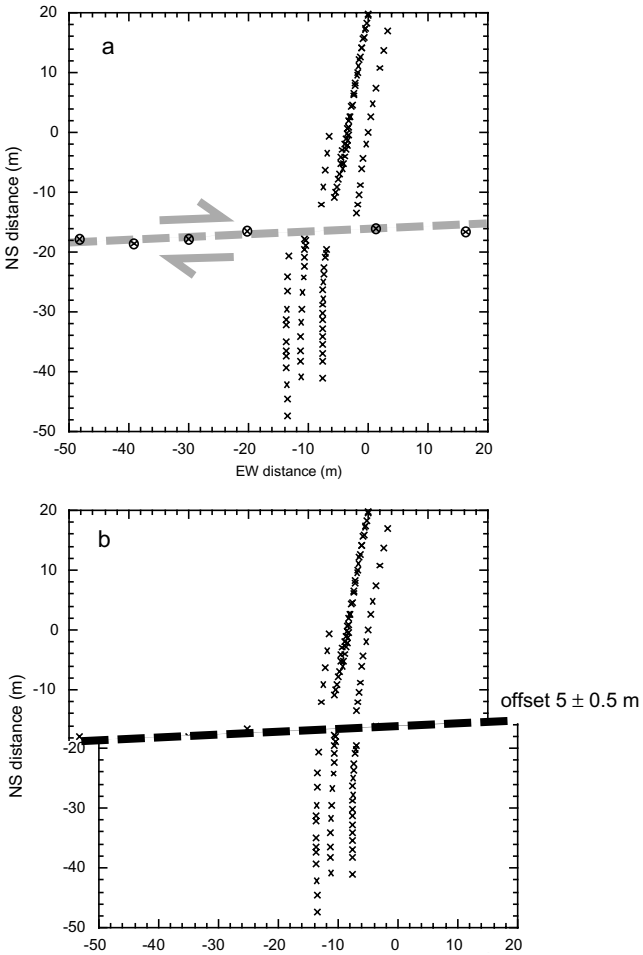

Figure 7. Survey with total station on Güven village road (site 2, for location see Fig. 2).

Bolu Mountain area to the eastern end of the rupture and disappears near the Bolu tunnel (Fig. 8).

The trace of the rupture clearly follows the older fault morphology in some places. Two offset streams were measured as 55 m and 12 m around Şimşir and east of Güven, respectively, which confirms the previous earthquakes (Fig. 2).

Slip Distribution of the 12 November Düzce Earthquake

The slip distribution of 12 November earthquake is shown in Figure 9. It appears that the average dextral offset is nearly 300 cm on a large part of the rupture. Maximum dextral slip is located on the central part of the rupture. The strike-slip displacement decreases sharply at both ends of the rupture. The western part of the rupture zone terminates at the Gölyaka pull-apart basin, where normal faulting is dominant. There are also some other vertical motions, normal faults, and thrust faults in the step-over areas along the Düzce rupture zone. These features are mostly shallow structures that occur in the upper part of the seismogenic zone. Even though a large normal component was observed in the teleseismic data, field observations indicated dominant strike slip and minor vertical motion along the main rupture zone.

Discussion and Conclusions

Figure 8 shows the large earthquakes around Bolu that occurred in the twentieth century, including 17 August and 12 November earthquakes. The 1957, 1967, and the western end of the 1944 earthquakes occurred on the southern part of the Almacık block. The August event occurred in a partly northwestern margin of the Almacık block, the Karadere segment, extending as far as Gölyaka. This easternmost segment of the August event (Karadere segment) had a maximum lateral offset of 150 cm (Hartleb *et al.,* 1999), and it ended with a couple of centimeters in the southwestern part of Eften Lake with a releasing step-over north of Gölyaka (Fig. 2). The 12 November 1999 Düzce earthquake caused a motion that overlapped about 9 km with the August rupture, having a maximum dextral offset of 300 cm and vertical offset of 350 cm in the southwest part of Eften Lake.

The November 1999 event caused rupture on the unbroken part of the fault mosaic surrounding the Almacık block three months after the August event. Considering the general westward migration of the North Anatolian fault since 1939, Barka (1996) predicted at least 1.5- to 2-m slip deficit in the west of Bolu, revealed from the comparison of the maximum slip that occurred during the 1944, 1957, and 1967 events; specifically, 3.5- to 4-m dextral slip was measured in the Bolu area resulting from the 1944 event, whereas the maximum slip in the Mudurnu valley changed between 1.6 and 2.6 m during the 1957 and 1967 events. However, the 5-m maximum slip is twice as high as the predicted slip along the 12 November rupture zone. This

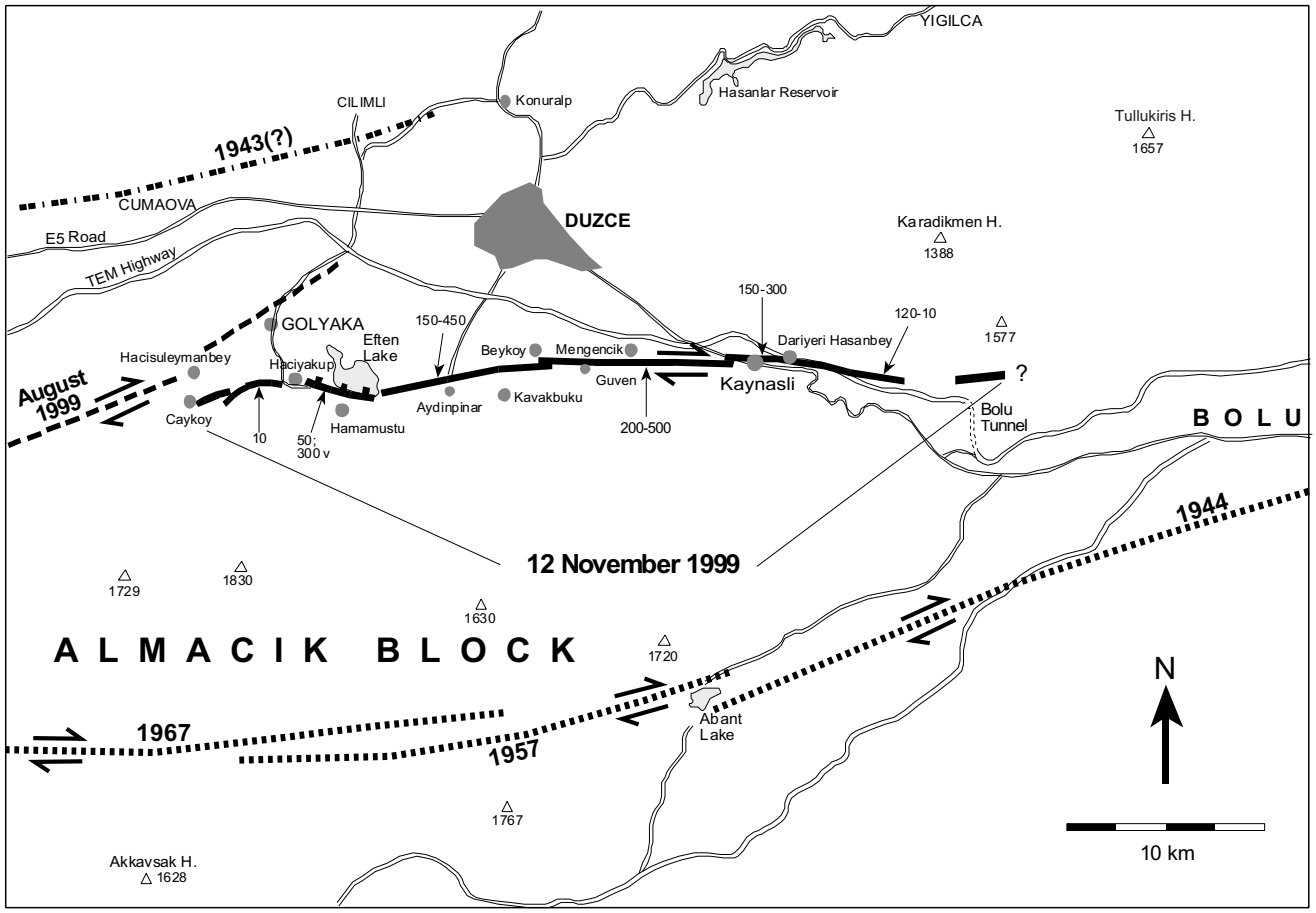

Figure 8. Active faults around Bolu. Numbers with arrow indicate lateral displacements; v, vertical separation.

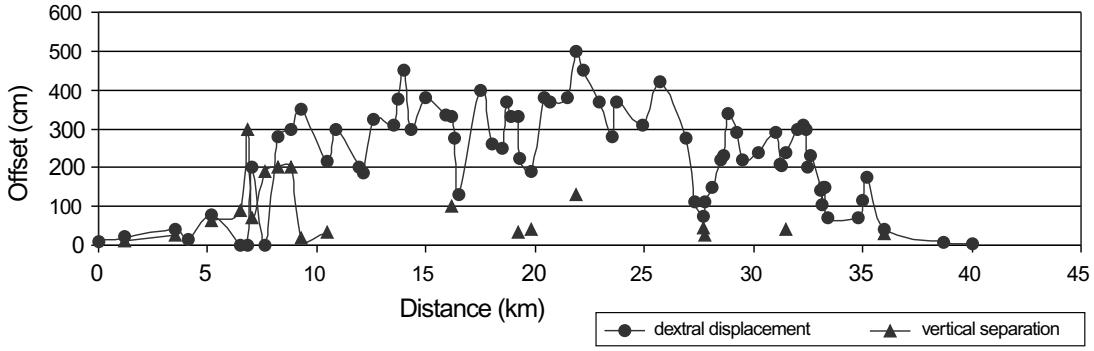

Figure 9. Slip distribution of the 12 November 1999 earthquake.

may suggest that the maximum slip along the 1944 was more than 4 m, perhaps as much as 6 m.

An unbroken part of 10–12 km between the eastern end of the Düzce fault and Bolu may still exist, which may cause a $M < 6.5$ earthquake. The other possibility is that this might have already ruptured during the 1944 earthquake.

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Manuscript received 14 November 2000.